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Axialization of calcium ions: Towards a Penning-trap quantum computer

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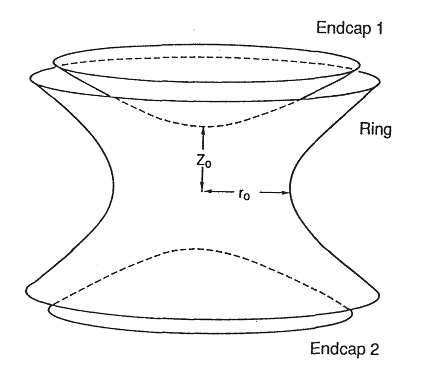
QUEST, QUBITS, QGATES

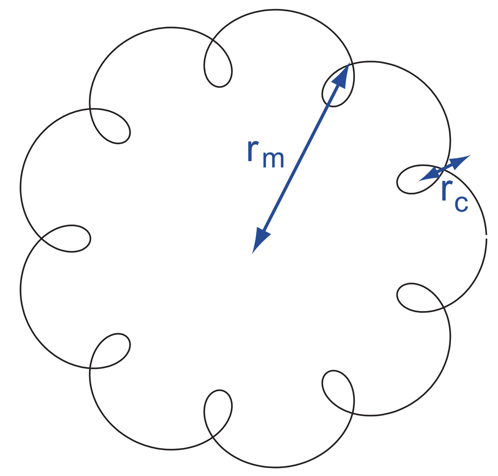
1. Introduction

Ion traps have been proposed as an ideal system in which to attempt small-scale quantum information processing (QIP). The demonstrations to date have been in radiofrequency (RF) traps. There can be heating of the ions as a result of micromotion caused by the trapping field. The Penning trap, which employs only static electric and magnetic fields, may allow lower heating rates of the ions and longer series of quantum gates.

A major disadvantage to the use of a Penning trap is the unbounded nature of one of the radial motions: the magnetron motion. This makes it difficult to laser cool the ions, and also to localise them as is required for many quantum computing schemes. We have overcome this problem by coupling the magnetron motion to the other radial motion, the modified cyclotron motion. This latter motion can easily be laser cooled.

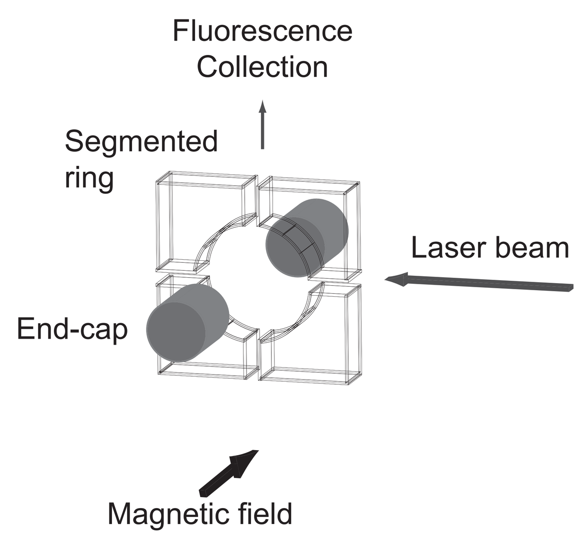


The Penning trap. The end-caps are kept at a positive potential with respect to the ring (to trap positive ions). An axial magnetic field provides radial confinement.

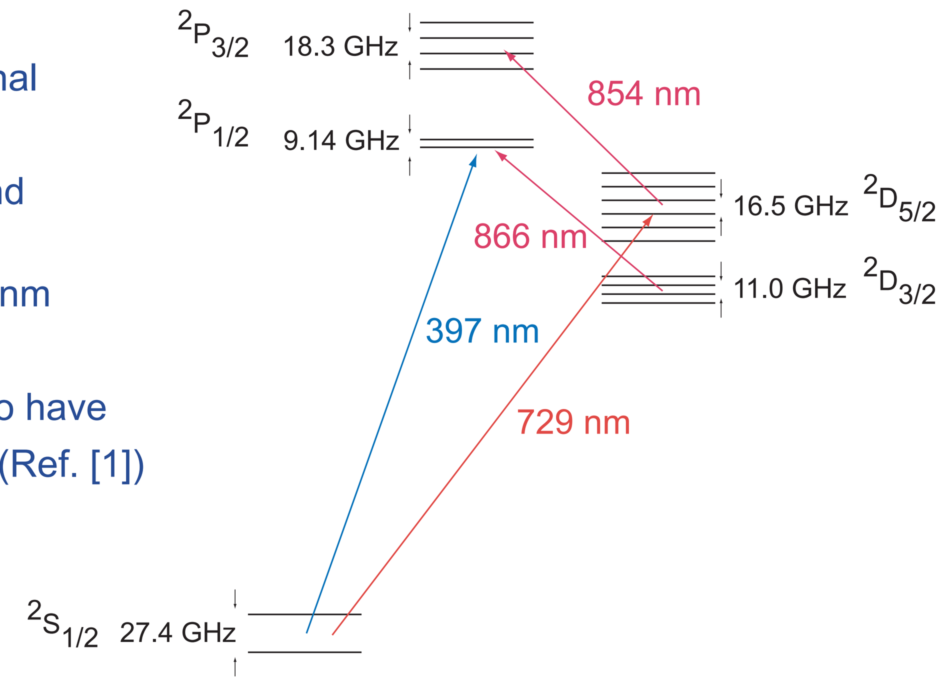


The radial motion. An epicycle formed by the slower magnetron motion (typically with a large radius) and the faster modified cyclotron motion

2. Doppler Cooling Ca^+ Ions



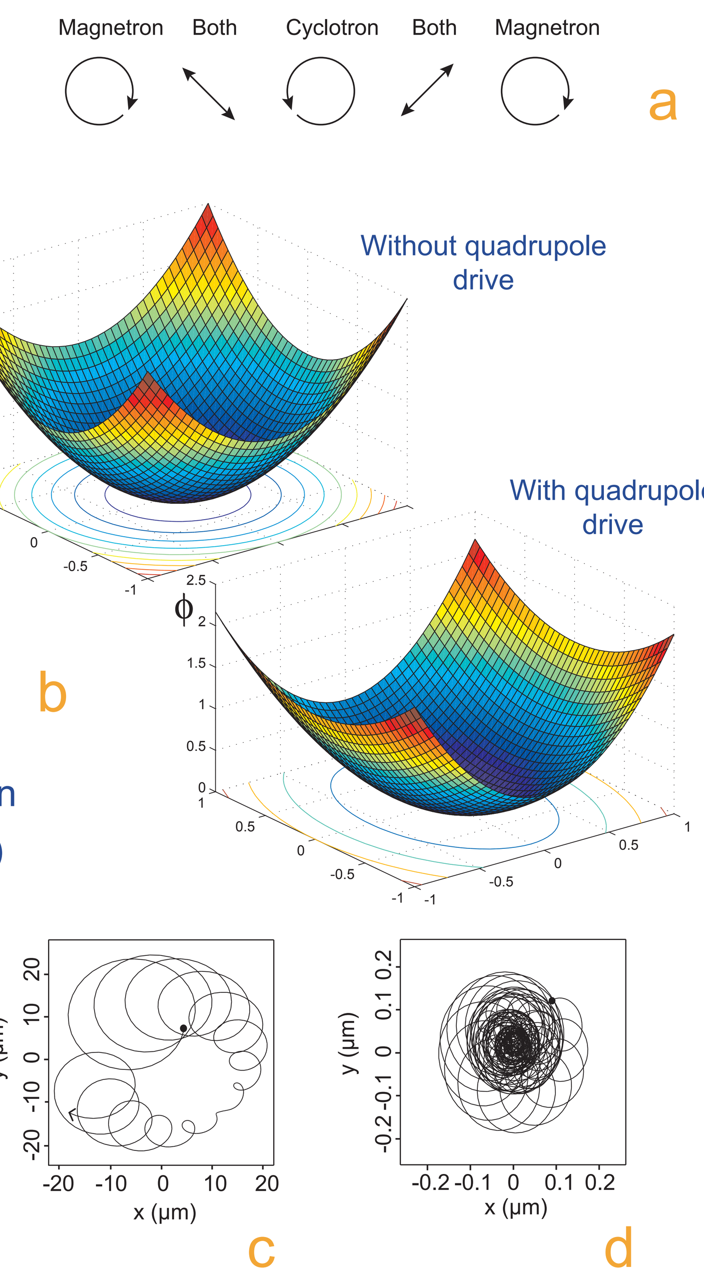
		Typical motional frequencies (kHz):
True cyclotron	$\omega_c = \frac{eB}{m}$	2π x 376
	$\omega_1^2 = \frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}$	
Modified cyclotron	$\omega_c' = \frac{\omega_c}{2} + \omega_1$	2π x 348
Magnetron	$\omega_m = \frac{\omega_c}{2} - \omega_1$	2π x 28
Axial	$\omega_z = \sqrt{\frac{4eU_0}{mR^2}}$	2π x 141



- Large Zeeman shifts mean additional lasers for cooling and repumping
- Diode lasers used for all cooling and repumping transitions
- Ti:Sapphire laser available for 729 nm transition
- First ion with metastable D states to have been laser cooled in Penning trap (Ref. [1])
- Final ion temperature < 1 K
- Difficulty trapping very small numbers of ions

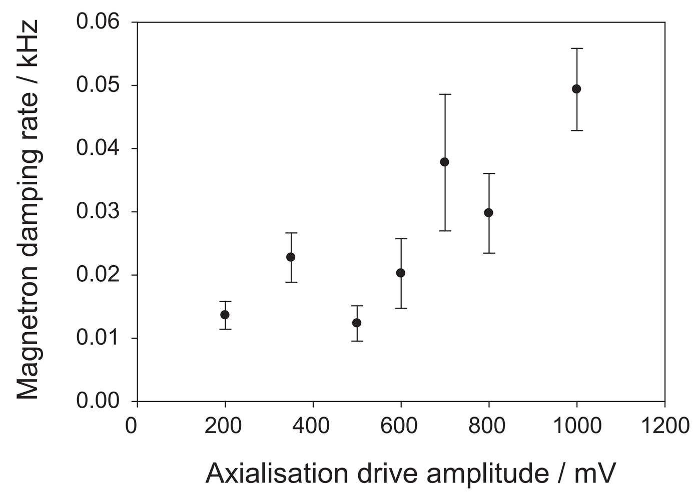
3. Axialization

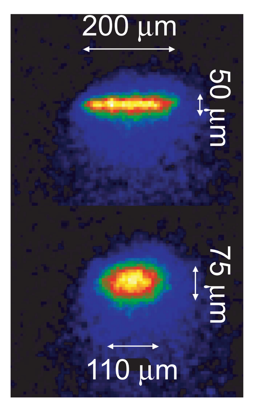
- In frame rotating at $\omega_c/2$, the two radial motions are circular but in opposite directions
- Typically, magnetron has large orbit and modified cyclotron has small orbit: combine to give elliptical orbit in rotating frame
- Apply azimuthal quadrupole coupling field with segmented ring electrode at sum frequency of motions:
  $$\omega_c' + \omega_m = \omega_c$$
- In rotating frame this has effect of compressing effective potential in one direction (see Fig. b)
- Typically motion evolves from being circular in one direction to linear and then to circular in other direction (see Fig. a)
- In lab frame observe evolution from pure magnetron to pure modified cyclotron motion and back (Fig. c)
- If one motion is damped, interconversion causes damping of other motion (Fig. d)
- Damping of modified cyclotron provided by laser cooling
- Magnetron consequently damped and ion forced towards axis of trap ("axialization").

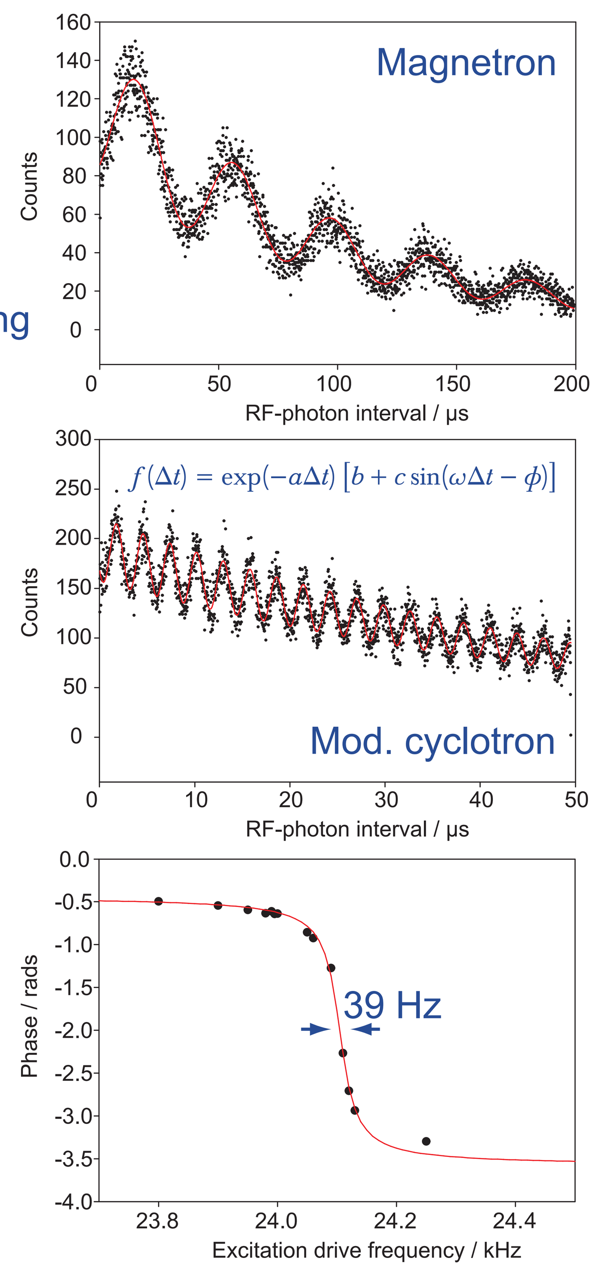


4. Damping Rates

- To measure damping rate, excite ion with signal near motional frequency
- Treat system as a forced damped harmonic oscillator
- Force comes from dipolar excitation voltage across ring
- Damping due to laser cooling
- RF-photon correlation measurement
- Phase of fitted function measured
- Plot phase as a function of excitation frequency
- Width of π phase change is the damping rate

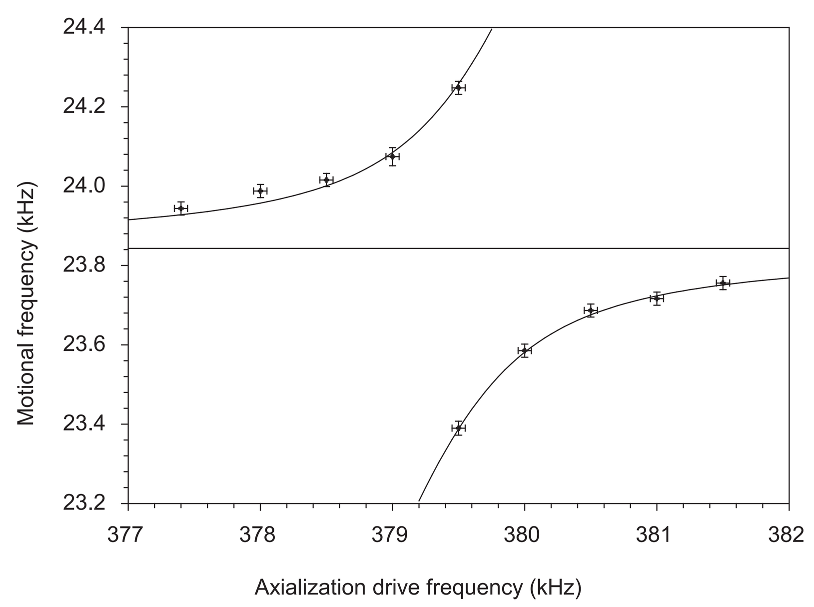


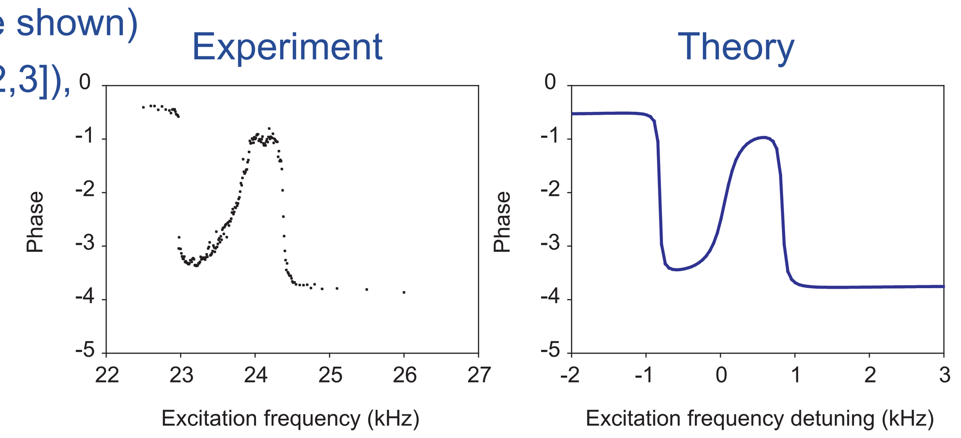




5. Classical Avoided Crossing

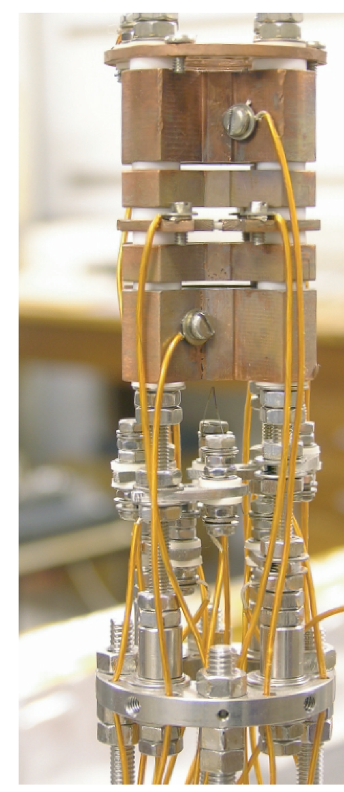
- Magnetron and modified cyclotron motions are classical coupled oscillators
- As the (coupling) axialization drive frequency is scanned through ω_c an avoided crossing is predicted
- Measured frequency (from fit of phase change) will deviate from uncoupled value as resonance is approached
- Previously observed with other pairs of coupled motions in Penning traps (Refs. [2,3])
- Centre frequencies determined from fits to phase plots
- Avoided crossing plot provides information on coupling rate (~900 Hz in example shown)
- Unlike previous observations (Refs. [2,3]), phase measurements were possible
- Excellent qualitative match with basic theory of classical coupled oscillators (Ref. [6])





6. Conclusions and Outlook

- Axialization in presence of laser cooling achieved with Ca^+ ions (previously only demonstrated with Mg^+ ions, Ref. [4])
- Ca^+ already shown elsewhere to be a viable candidate for ion-trap quantum computing (Ref. [5])
- Tighter confinement and more efficient cooling vital for investigation of suitability of ions in a Penning trap for QIP
- Future goals include trapping of single Ca^+ ions in a Penning trap
- Previous experience with Mg^+ suggests trapping single ions easier in presence of axializing field
- Next stage is to trap in a superconducting magnet and probe narrow quadrupole transition (729 nm)
- Pound-Drever-Hall stabilised Ti:sapphire laser now available for this purpose (current linewidth ~ 3kHz)
- Rabi flops and motional sidebands will give indication of heating and decoherence rates in trap



Cylindrical Penning trap for use in the bore of a superconducting magnet

References

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[3] Häffner et al., European Physical Journal D **22** (2003) 163-182

[4] H. F. Powell et al., Journal of Physics B **36** (2003) 961-970

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